

ACCELERATOR PHYSICS ISSUES FOR THE VERY LARGE HADRON COLLIDER

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Abstract

The goal of the Very Large Hadron Collider (VLHC) is to extend the energy frontier beyond LHC. The proposed design center of mass energy for the VLHC pp collider is 100 TeV, with a luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$ and an integrated luminosity of about 100 fb^{-1} per year. In this paper we present a summary of work conducted during a workshop and issues we feel are most important. Accelerator Physics issues and design aspects specific to both the high field and low field magnet technologies were studied, including general accelerator parameters, beam stability issues, magnet field quality and the R&D needed to relax the accelerator component tolerances. This paper summarizes the accelerator physics R&D the VLHC Accelerator Physics Working Group members are undertaking.

1 INTRODUCTION

Hadron Colliders are the "Discovery Machines" for high-energy physics. The high-energy physics (HEP) and accelerator physics communities are working together to extend the energy frontier beyond LHC. A very large hadron collider is a machine we know can be built today. The main issue is cost. Considerable R&D are needed in Accelerator Technology and in improving our understanding of Accelerator Physics to reduce the overall cost of the accelerator construction and operation.

The VLHC magnet R&D groups are investigating two different magnet technologies: high field (10-12 Tesla) [1-5] and low field (2 Tesla) [6]. The magnetic field quality at injection, eddy and persistent currents and hysteric effects limit the ratio of energy at collision increase to injection for a synchrotron. We have assumed this factor to be 20 for accelerator design.

The U.S. site for the VLHC is assumed to be Fermilab. We are planning to use the Fermilab injection chain of the Linac (400 MeV), Booster (8.9 GeV) and the newly commissioned Main Injector (150 GeV). These three are rapid cycling accelerators. The Main Injector can cycle to 150 GeV in about 2.4 sec. The Main Injector will be used as an injector in the VLHC. The VLHC will have two new accelerators, a 3 TeV High Energy Booster (HEB) and a 50 TeV, pp collider. Counter rotating protons will

be injected into the HEB by extracting protons from the Main Injector at MI40 and MI61.

There are several ways to categorize the accelerator physics issues for the VLHC. In this paper we choose to categorize them as single particle, multi-particle and energy deposition issues. Considerable experience has been gained in the past two decades of hadron collider operations and recent design efforts of the SSC and LHC. At present the VLHC efforts are predominantly on magnet technology and the R&D effort is a collaboration of national laboratories and industries. The accelerator physics R&D efforts are to support these technologies R&D effort for a final usable product.

2 SINGLE PARTICLE ISSUES

The single particle issues are concentrated on the basic accelerator design, i.e. lattice design, magnet quality, aperture requirements, correction system and schemes. The issues range from the basic cell length to the effect and benefit of synchrotron radiation.

The most fundamental question that needs to be addressed is the magnet field quality and aperture of the magnet at injection. For all magnet designs both the cost and the field quality are reduced as aperture decreases. With magnet cost expected to be an even more dominant component of VLHC costs than in any previous machines, accelerator physics will play a crucial role in the economic feasibility of the machine.

The mechanical construction of the high field magnet determines the field quality at full excitation. The field quality of Nb-Ti magnets has improved significantly in the last few years due to improvements in manufacturing, changes in design and reduction in measurement errors. The magnet production techniques have improved so that the random errors can be controlled to the point where systematic effects dominate. However at injection energy the field defects of high field magnets will be dominated by persistent current magnetization defects which depend on both excitation history and time.

For the low field option the field quality challenges occur at top energy as the iron enters saturation. At the 1-kG injection field the iron is above the point where

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remnant fields dominate. The field quality of the low field option needs detailed studies. At present we have no data on the field quality of the low field magnet. Dynamic aperture calculations will be performed when field measurement data become available.

The cell length of the lattice has two competing effects. If random errors dominate, shorter cell lengths would be preferred while the opposite is true if systematic errors were dominant [7]. The cell length also has implications on the acceptable size of the magnetic higher order systematic multipoles. A calculation performed [8] with a study lattice (Figure 1) show that smaller cell length is preferred to relax the systematic multipole requirements. We need to perform calculations to find an optimal balance between the cell length, allowed systematic and random multipoles for a realistic aperture R&D magnet.

The high field option design has an advantage at collision energy due to synchrotron radiation damping. The damping time is smaller than the storage time. Figure 2. shows that the emittance of the bunch decreases as a function of store time due to synchrotron radiation [9]. The luminosity of the collider is enhanced for relatively modest bunch intensity. This effect only helps the magnet design and quality at high energy. The aperture and magnetic field errors at injection energy for both the high field and low field option need to be investigated by simulations. The beneficial effects of damping due to synchrotron radiation in the high field option should not be relied on to relax the requirements on the error fields at injection.

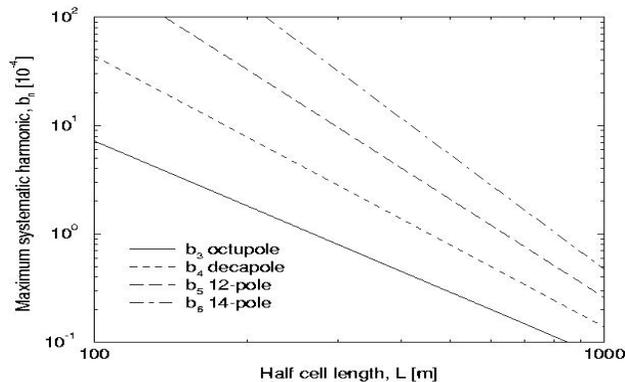


Figure 1. Maximum allowable systematic harmonics vs. half cell length, when $\Delta Q_x = 0.1$, $\phi_c = 90$ degrees, $\epsilon_x = 1 \mu\text{m}$, at an energy of 1 TeV, with a reference radius of 16 mm

An error budget for the dipole, quadrupole, sextupole, octupole and misalignments of the magnetic elements needs to be developed. The distribution of the dipole correctors has implication on the allowed size of the closed orbit error and hence on the beam pipe aperture. It is an important issue to determine how the minimal distance between dipole correctors scales with the parameters of the ring such as the energy, circumference, cell length, phase advance and aperture size. Based on the LHC simulation experience the higher order nonlinear correctors can be placed at well-chosen locations in the arcs. Simulations performed show that for this method to

be effective, an experimental measurement of the one turn map is required.

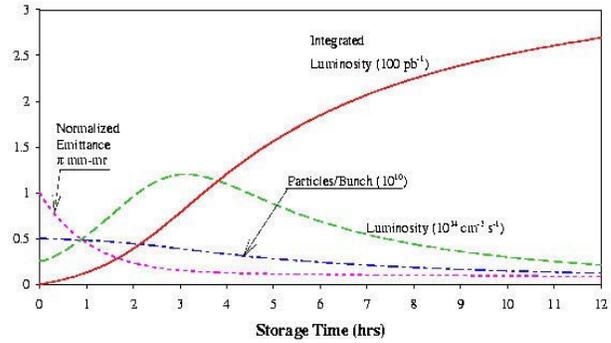


Figure 2. Beam parameters during a store for high-field VLHC.

The effects of ground motion on lattice design and machine performance need to be studied. Ground motion studies are being carried out at different laboratories and in the strata under Fermilab [10].

3 MULTI PARTICLE ISSUES

The effects of multi-particle dynamics will be an area of considerable R&D for both magnet technologies. Because of the large circumference of these machines, transverse instabilities tend to dominate. Since the Snowmass 96 workshop this has been a topic of interest because considerable attention needs to be paid to reduce or eliminate the effects of these instabilities in an accelerator design. None of these instabilities are considered as a “show-stoppers”, but the low field magnet design has lower thresholds. There appears to be enough current state of the art technique to damp or eliminate all of these instabilities. Detailed description of R&D to study these instabilities and proposed ideas to reduce their effect can be found in ref [11].

The Transverse mode coupling instability (TMCI) also known as “strong head-tail” are due to the shift of the coherent bunch motion $m = 0$ and head-tail motion $m = 1$ by the broadband transverse impedance. This instability has been observed at many electron storage rings (which normally operates with bunch length in mm range) but has not been observed in proton colliders (with bunch length in tens of cm). The calculated safety factor (SF) for TMCI is 1.1 and 28 for the low field (LF) and high field options respectively [11]. This is an improvement over the previously calculated value by a factor of two [12]. This is due to several parameter optimized for the low field design. There are several innovative ideas to increase the threshold of TMCI beside the obvious but costly ones like decreasing the circumference, increasing the beam pipe aperture or increasing the injection energy. One scheme of filling the Low Field (LF) machine from the Main Injector is to fill every 9th bucket. At injection one can reduce the intensity per bunch by nine times and fill every bucket. This could help increase the SF to about 9. Then one will have to coalesce bunches at high energy before collision. The TMCI SF also can be increased by about factor of 4 by using RF quadrupoles, which introduces

correlated tune, spread from the head to the tail of the bunch. Using an AC sextupole scheme to increase the lattice chromaticity can increase the SF by about 10. The effect of RF quadrupoles and AC sextupoles on the dynamic aperture needs to be studied, because they could potentially excite resonance. A relatively small amount of gain in threshold is possible by coating the beam tube and by using an asymmetric beam tube. The TMCI threshold can be further increased by a factor of 5 or more by implementing a feed back system. It seems likely that TMCI will impose luminosity ceiling above 10^{35} even for the low field machine.

The coupled-bunch instability at injection has a growth time of 1.5 turns and 180 turns for the LF and HF designs respectively. Since the growth time of this instability is on the order of a single turn a distributed damping system has been proposed [11].

Other instabilities, which are being studied, are 1) electron cloud instability at 50 TeV, 2) coherent synchrotron tune shift at 50 TeV and 3) longitudinal microwave instabilities at 50 TeV. These instability studies need to develop along with the design of the machine lattice and need to be folded together in an overall design of the VLHC.

We need to understand these instabilities by careful experiments. Possible experiments are being examined for the Tevatron to excite TMCI in a proton machine and at VEPP-4M to study the effect of RF quadrupoles on TMCI.

4 ENERGY DEPOSITION ISSUES

In the design of any accelerator the operational and environmental radiation limits must be considered to determine the required accelerator tunnel depth, tunnel wall thickness and other protective measures like beam collimation, beam abort and beam dump design. The R&D and design efforts are progressing on radiation protection systems for two types of beam loss in the collider, operational and accidental [13]. In all colliders beam-gas interaction, intra-beam scattering, interactions at the IP, noise and other imperfections produce a beam halo. This beam halo interacts with the limiting aperture and produces radiation for the accelerator and background for detector elements. A collimation system is required to reduce the effect of operational beam loss. R&D on the collimation system design needs to progress in parallel with the lattice design. The stored beam energy in the accelerator is very large and beam size is very small at these energies. An accidental loss of a small fraction of beam during a short time will melt a hole through the magnet and can cause damage to the accelerator components. The beam abort system and beam dump needs to be developed and integrated into the machine lattice.

5 SUMMARY

The VLHC accelerator physics R&D program is being developed in collaboration with four laboratories, FNAL, LBNL, BNL and several universities in the U.S. Several

calculations and design simulations are already underway. This paper summarizes some of the issues we have start working on. This list is by no means complete. We are working together with the Magnet Technology and Accelerator Technology working groups towards the goal of a less expensive and cost-efficient hadron collider.

Almost all single particle issues and energy deposition issues are important to both the low and high field magnet designs. Since the magnet technologies are still being developed it might be premature to find an optimal solution for the VLHC design. But on the other hand we need to develop our understanding of hadron collider accelerator physics by modeling. We need to propose carefully planed experiments at existing hadron colliders to validate these theories.

The authors will like to thank everyone who contributed to the VLHC Accelerator Physics Workshop, which was held at Lake Geneva, WI, Feb 22-25, 1999, under the VLHC Steering Committee (<http://vlhc.org>).

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